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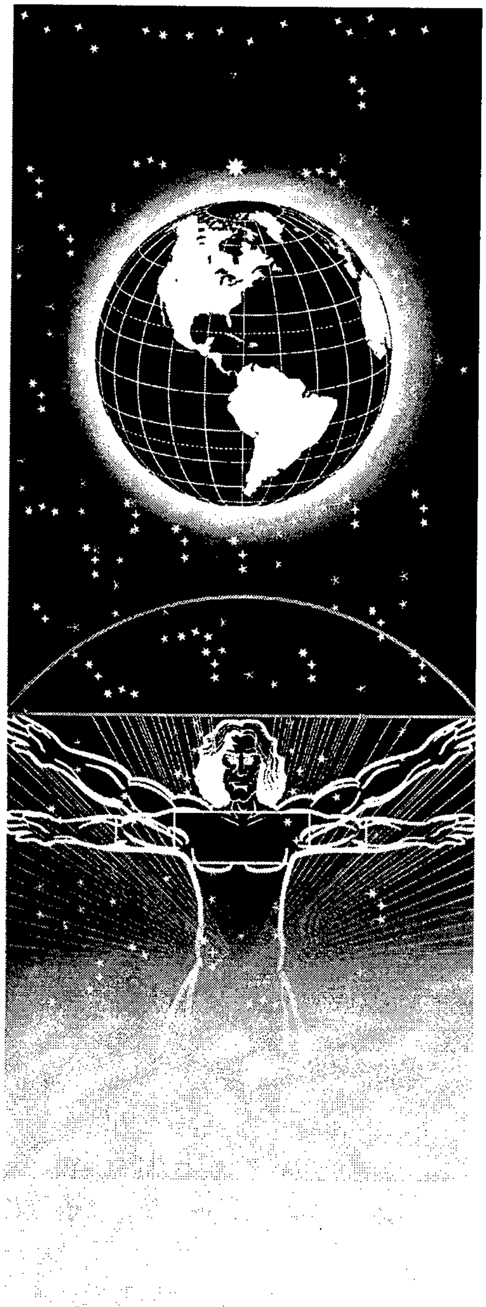

# UNITED STATES AIR FORCE
# ARMSTRONG LABORATORY

## Maintenance Hazard Simulation: A Study of Contributing Factors

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This paper has been reviewed and is approved for publication.

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This paper develops a foundation for the representation of hazardous conditions for animated maintenance simulation. Specifically, the objective of this study was to furnish methods to calculate and display hazard thresholds in a simulation system called DEPTH (Design, Evaluation for Personnel, Training, and Human Factors). DEPTH allows maintenance procedures to be graphically simulated using three-dimensional Human Figure Models (HFM) and computer-aided design geometry. By integrating existing equations and data to generate hazardous regions, DEPTH will be able to indicate when a human figure comes too close to an "unsafe" object. Once the capability is incorporated in DEPTH, it will be possible to develop safer weapon systems and maintenance procedures. This study focused on radiant and contact properties of objects including operating temperature, voltage, and noise as opposed to ambient factors such as arctic or tropical conditions.

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# Maintenance Hazard Simulation: A Study of Contributing Factors


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## Abstract

This paper develops a foundation for the representation of hazardous conditions for animated maintenance simulation. Specifically, the objective of this study was to furnish methods to calculate and display hazard thresholds in a simulation system called DEPTH (Design, Evaluation for Personnel, Training, and Human Factors). DEPTH allows maintenance procedures to be graphically simulated using three-dimensional Human Figure Models (HFM) and computer-aided design geometry. By integrating existing equations and data to generate hazardous regions, DEPTH will be able to indicate when a human figure comes too close to an "unsafe" object. Once the capability is incorporated in DEPTH, it will be possible to develop safer weapon systems and maintenance procedures. This study focused on radiant and contact properties of objects including operating temperature, voltage, and noise as opposed to ambient factors such as arctic or tropical conditions.


## Introduction

The DEPTH software provides maintenance analysis tools for evaluating logistics support requirements. In the design process, the time and cost required to modify a system's configuration can be significantly less using DEPTH compared to a fabricated mockup. By the time physical mockups are built, it is often too late to make changes for maintainability issues. DEPTH simulates a variety of man-machine interface tasks during design processes allowing necessary changes to be made before design implementation. Using DEPTH's HFM, designers can evaluate alternate system configurations and procedures to optimize maintainability. For example, designers can evaluate a removal operation as depicted by DEPTH's HFM in Figure 1.

Several factors are considered in maintenance simulation analyses. Many HFM programs determine if a human can reach an object and some even evaluate human strength limitations. However no graphical simulation determines when the HFM contacts or is in range of a potential hazard.

Given the importance of workplace safety, weapon system developers have expressed a need to evaluate

Figure 1. DEPTH's HFM removing a B-1B component.



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these factors in HFM simulations. For example, do maintainers troubleshoot a system in a noisy environment that requires ear protection? Will they be exposed to a heat source during a maintenance task? Will technicians be exposed to a high level of radio frequency or microwave radiation?

With HFM simulations, it is possible to display hazard conditions in real time. *Jack®* [14], the articulated figure modeling system integrated into DEPTH, can be used to demonstrate cumulative effects of simulated radiant objects on HFMs with respect to the amount of hazard source potential, distance from hazard source, and time exposed. Simulated hazard results are given both numerically and visually by computation and gradual changes in the color around the affected areas, respectively. Figure 2 displays how radiant effects can be projected onto surfaces in close proximity to a hot valve. The projections from the source onto the arms and pipe are simulated using color changes.

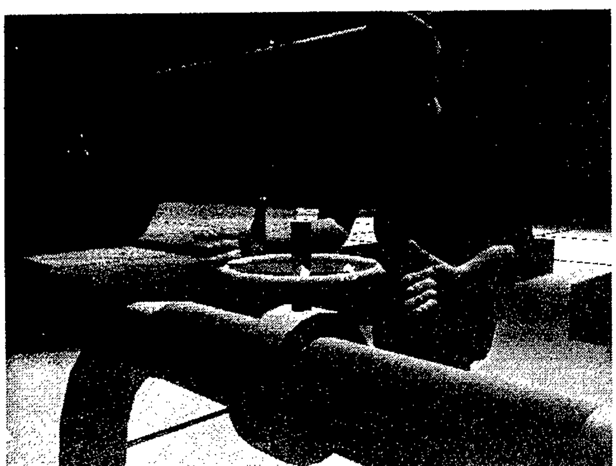

Figure 2. Projection of radiant effects.

A hazard's radiant properties and the human exposure limits are dependent on the amount of energy of the source, distance from the HFM to the source, and total exposure time. This concept is important for simulation purposes because the technique used to evaluate each hazard can be similar. Thus, the programmer implementing this functionality for DEPTH is not required to write special code for heat, noise, and other radiant effects. The DEPTH simulation will govern each condition in the same manner with the exception of the propagation algorithm and data used to evaluate exposure limits.

This study concentrated on evaluating existing formulas and data which provide DEPTH with relevant information to assess simulated hazards. The formulas and data may be used for computing the resulting exposure effects by the HFM and warning the user of high risk exposures.

The user will also be able to define their own regions independent of the algorithms in this study. An organization may have its own safety policies that are more or less restrictive than those stated in this report. Or there may be a need to simulate hazards that are not covered in this paper. For example, the intake of an operating jet engine is a significant hazard. A region around the engine should be defined as a hazard, but this is beyond the scope of this study.

## Method

A search of hazard information including databases, military standards and industry standards was conducted to locate algorithms and data regarding human exposure limits. Over 4000 abstracts were collected and 47 references reviewed. Relevant environmental data and algorithms relating to human exposure limits for current, voltage, illumination, noise, vibration, temperature, microwave radiation, radio frequency radiation, x-radiation, gamma radiation, and ultraviolet radiation were collected.

## Results

Table 1 presents the environmental data and algorithms consolidated for DEPTH. The categories studied are discussed in the following sections.

### Current and Voltage

Specifications for safe exposure limits to electrical current and voltage were developed based on Hammer's [6] resistance values for wet and dry hands. As described by Hammer, electrical current will stream through the body when it contacts a voltage or current source. DEPTH's HFM will display a warning message when electrical shock is probable, and manifest a distinct color for all objects possessing dangerous current or voltage levels.

### Lighting Conditions

Military Standard 1472-D [9] provides specifications for illumination including minimum lighting requirements. For a particular maintenance task, the illumination algorithm described in Table 1 provides the maximum allowable distance ($D_{max}$) from the source to the work surface. If the actual distance is greater than $D_{max}$, then DEPTH will display a warning message

specifying that low illumination levels exist for a particular maintenance task.

## Noise

Noise level limits, developed by OSHA [10], are used to describe two grades of hazards. The first hazard level, 80 dB or greater but less than 115 dB, permit short-term human exposure. The second hazard level, 115 dB or greater, is the maximum human exposure limit. Colored, transparent spheres emanating from each noise source determine the boundaries of each noise hazard in the DEPTH simulation. Future DEPTH versions may calculate the eight-hour time-weighted average (TWA) sound level.

## Wind Chill Factor

The wind chill temperature, as defined by ASHRAE [2], provides a reliable method to express the combined effects of wind velocity and air temperature. If the wind chill temperature falls below safe exposure limits, then DEPTH will warn the user that the HFM is being exposed to freezing temperatures.

## X-Radiation and Gamma Radiation

Maximum exposure limits for x-radiation and gamma radiation as defined by Cheever [3] are represented by graphical radiation hazard shells which define the minimum distance a human should operate from a radiation source. Dissipated radiation is dependent upon the source material.

## Microwave, Radio and Ultraviolet

Maximum exposure limits for microwave and radio frequency radiation as defined by IEEE C95.1 [7], and ultraviolet radiation as defined by Largent, Olishifski and Anderson [8] and ACGIH [1] are given in Table 1. The algorithms for these environmental conditions are dependent upon several "look-up" tables.

**Table 1.** Environment Data and Algorithms

| Condition | Inputs | Algorithm | Output |
|---|---|---|---|
| Current [6] | 1. I = Current source in amperes<br>2. Check to see if the source is alternating current (AC) or direct current (DC) | Safety threshold limit values:<br><br>AC ≤ 4 mA<br>DC ≤ 15 mA | If there is an alternating current source, then current (I) should be ≤ 4 mA, else a warning message is provided: **"Danger, Electrical Shock Probable."**<br><br>If there is a direct current source, then current (I) should be ≤ 15 mA, else a warning message is provided: **"Danger, Electrical Shock Probable"** |
| Voltage [6] | 1. V = Voltage of the source in volts.<br>2. Check to see whether the hand is wet or dry.<br>3. Check to see if the source is alternating current (AC) or direct current (DC). | Wet Hand Voltage Conversion Algorithm:<br>**I = V / 15,000Ω**<br><br>Dry Hand Voltage Conversion Algorithm:<br>**I = V / 400,000Ω**<br><br>Variables:<br>V= Voltage in volts<br>I = Current in amperes | If there is an alternating current source, then current (I) should be ≤ 4 mA, else a warning message is provided: **"Danger, Electrical Shock Probable."**<br><br>If there is a direct current source, then current (I) should be ≤ 15 mA, else a warning message is provided: **"Danger, Electrical Shock Probable."** |

**Table 1.** Environment Data and Algorithms (continued)

| Condition | Inputs | Algorithm | Output |
|---|---|---|---|
| Lighting Conditions [9] | 1. I = Intensity of the source in candela (cd)<br>2. D = Distance from the source to the surface in meters.<br>3. $L_R$ = illumination requirements for surface at which the **specific task** is being performed in lux (lx)<br><br>Note: $L_R$ is defined by MIL-STD 1472D. | Illumination Algorithm, Inverse square law:<br>$\mathbf{D_{Max} = (I / L_R)^{1/2}}$<br><br>Additional Variable:<br>$D_{Max}$ = Maximum allowable distance from the source to surface, in meters (m)<br><br>Other relevant equations:<br>1 cd = 12.57 lm<br>1 lx = 1 lm/m$^2$<br>1 fc = 1 lm/ft$^2$<br>1 fc = 10.76 lx | If the distance (D) is greater than $D_{max}$, then a warning message is provided: **"The illumination level is too low for this working condition."** |
| Noise [10] | 1. dB0 = Noise level measured 10 cm from the source. | 80 dB Hazardous Shell Radius Algorithm:<br>$\mathbf{R_1 = 0.1 * ( 10^{(dB0 - 80)/10})^{1/2}}$<br><br>115 dB Hazardous Shell Radius Algorithm:<br>$\mathbf{R_2 = 0.1 * ( 10^{(dB0 - 115)/10})^{1/2}}$<br><br>Variables:<br>dB0 = Noise level measured 10 cm from the source<br>$R_1$ = the radius of the hazard shell in meters for a 80 dB sound level<br>$R_2$ = the radius of the hazard shell in meters for a 115 dB sound level | $R_1$ = the radius of the hazard shell in meters for a 80 dB sound level.<br><br>If human is inside of $R_1$, then a warning message is provided: **"Caution, *human* is entering noise area."**<br><br>$R_2$ = the radius of the hazard shell in meters for a 115 dB sound level<br><br>If human is inside of $R_2$, then a warning message is provided: **"Danger, *human* is entering high level noise area that exceeds safety threshold."** |

**Table 1.** Environment Data and Algorithms (continued)

| Condition | Inputs | Algorithm | Output |
|---|---|---|---|
| Wind Chill Factor [2] | 1. V = wind velocity in m/s<br>2. $t_a$ = ambient air temperature in deg C | Wind chill temperature algorithm:<br>$\mathbf{t_{eq} = -0.04544 * [(10.45 + 10*V^{1/2} - V) * (33 - t_a)] + 33}$<br><br>Note: This equation is not reliable if V > 22.2 m/s.<br><br>Variables:<br>V = Wind velocity in m/s (equation only reliable if V < 22.2 m/s)<br>$t_a$ = Ambient air temperature in deg C<br>$t_{eq}$ = Wind chill temperature in deg C | If $t_{eq}$ is < 0, then a warning message is provided: **"Danger, *human* is being exposed to a below freezing temperature."** |
| Radio [7] | 1. f = frequency. | Refer to Table 2. The algorithm depends upon the frequency of the source.<br><br>Variables:<br>E = electric field strength<br>H = magnetic field strength<br>S = power densities (S), and induced currents, as they relate to a specific frequency<br>f = frequency (MHz) | If a radio radiation source is present, then a warning message is provided: **"Danger, *human* is being exposed to radio frequency radiation. The time exposure limit is (t)."**<br><br>Note: The DEPTH program will calculate the exposure time limit (t) based on Table 2. |
| Microwave [7] | 1. S = power density, $W/cm^2$<br>2. f = frequency. | Refer to Table 3. The algorithm depends upon the frequency of the source and type of environment.<br><br>Variables:<br>E = electric field strength<br>H = magnetic field strength<br>S = power densities (S), and induced currents, as they relate to a specific frequency<br>f = frequency (MHz) | If power density > 500 $W/cm^2$, then a warning message is provided: **"Danger, *human* is being exposed to high levels of microwave radiation."**<br><br>If power density < 100 $W/cm^2$, then there is no limit on time of exposure. A warning message is not required.<br><br>If power density > 100 $W/cm^2$ and less than 500 $W/cm^2$ , then the DEPTH program will calculate exposure time limits based on Table 3. |

**Table 1.** Environment Data and Algorithms (continued)

| Condition | Inputs | Algorithm | Output |
|---|---|---|---|
| X-radiation [3] | 1. Number of Roentgens per hour given off by the source<br><br>2. Maximum Permissible Dose in Roentgens per hour | X-Radiation Hazard Shell Radius Algorithm:<br>**$d = ((R/hr)/MPD)^{1/2}$**<br><br>Variables:<br>d = distance in feet<br>R/hr = Roentgens per hour<br>MPD = Maximum Permissible Dose in R/hr | If human < d from the source, then a warning message is provided: **"Danger, *human* is being exposed to high levels of X-radiation."**<br><br>If human ≥ d from the source, a warning message is not required. |
| Gamma Radiation [3], [13] | 1. Name of the radioactive source and its quantity (or activity) in curies (C)<br><br>2. E = energy being emitted by the radioactive source<br><br>3. F = fractional yield<br><br>4. Maximum Permissible Dose in Roentgens/week | Allowable Dose Rate Per Hour Algorithm: **$A = MPD/40$ hours**<br><br>Retrogen Per Hour at 1 Foot Algorithm:<br>**$R/hr$ at 1 ft $= (6)\ C*E*F$**<br><br>Gamma Hazard Shell Radius Algorithm:<br>**$d = (R/hr \text{ at 1 foot}/A)^{1/2}$**<br><br>Variables:<br>R = Roentgens<br>C = strength of the source in curies<br>E = gamma-radiation energy in MeV<br>F = fractional yield of gamma-radiation per disintegration<br>d = gamma hazard shell radius in feet<br>MPD = Maximum Permissible Dose in R/week<br>A = allowable dose rate per hr. | If human < d from the source, then a warning message is provided: **"Danger, *human* is being exposed to high levels of gamma radiation."**<br><br>If human ≥ d from the source, a warning message is not required. |
| Ultraviolet [1], [8] | 1. $\lambda$ = wavelength<br><br>2. E = total irradiance<br>OR<br>$E_{eff}$ = effective irradiance | **For $\lambda$ of 320 nm to 400 nm** and $E < 1$ mW/cm$^2$<br>t = 1000 sec.<br><br>**For $\lambda$ of 200 to 315 nm**, with $E_{eff}$ known<br>**$t = 0.003$ J/cm$^2$/ $E_{eff}$**<br><br>Variables:<br>E = total irradiance<br>$E_{eff}$ = effective irradiance in W/cm$^2$<br>$\lambda$ = wavelength in nm<br>t = time exposure limit in seconds | If an ultraviolet radiation source is present, then a warning message is provided: **"Danger, *human* is being exposed to ultraviolet radiation. The time exposure limit is (t)."** |

**Table 2.** Maximum Permissible Exposure of Radio Frequency Radiation [7]

| Frequency Range (MHz) | Electric Field Strength (E) (V/m) | Magnetic Field Strength (H) (A/m) | Power Density (S) E-Field (mW/cm^2) | Power Density (S) H-Field (mW/cm^2) | Average Exposure Time \|E\|^2, \|H\|^2 or S (minutes) |
|---|---|---|---|---|---|
| 0.003 - 0.1 | 614 | 163 | 100 | 1000000 | 6 |
| 0.1 - 3 | 614 | 16.3 / f | 100 | 10000 / f^2 | 6 |
| 3 - 30 | 1842 / f | 16.3 / f | 900 / f^2 | 10000 / f^2 | 6 |
| 30 - 100 | 61.4 | 16.3 / f | 1 | 10000 / f^2 | 6 |
| 100 - 300 | 61.4 | 0.163 | 1 | 1 | 6 |
| 300 - 3000 | | | f / 300 | f / 300 | 6 |
| 3000 - 15000 | | | 10 | 10 | 6 |
| 15000 - 300000 | | | 10 | 10 | 616000 / f^1.2 |

f = frequency in MHz

**Table 3.** Maximum Permissible Exposure of Microwave Radiation [7]

| Frequency Range (MHz) | Power Density (S) E-Field (mW/cm^2) | Power Density (S) H-Field (mW/cm^2) | Average Exposure Limit (minutes) |
|---|---|---|---|
| 300 - 3000 | f / 300 | f / 300 | 6 |
| 3000 - 15000 | 10 | 10 | 6 |
| 15000 - 300000 | 10 | 10 | 616000 / f^1.2 |

f = frequency in MHz

## Conclusion

This report has discussed preliminary research in this area; more research and development is needed before hazard simulation is available for general use. Visual simulation and graphical environments provide designers with new techniques to simulate the effects of environmental factors. HFM systems, such as DEPTH, can provide real-time graphical assessments of hazardous properties and objects. Hazard shells can define the boundaries of regions for the human to avoid. These boundaries, as illustrated in Figure 3, can also be used to monitor cumulative effects and warn when protective equipment should be used.

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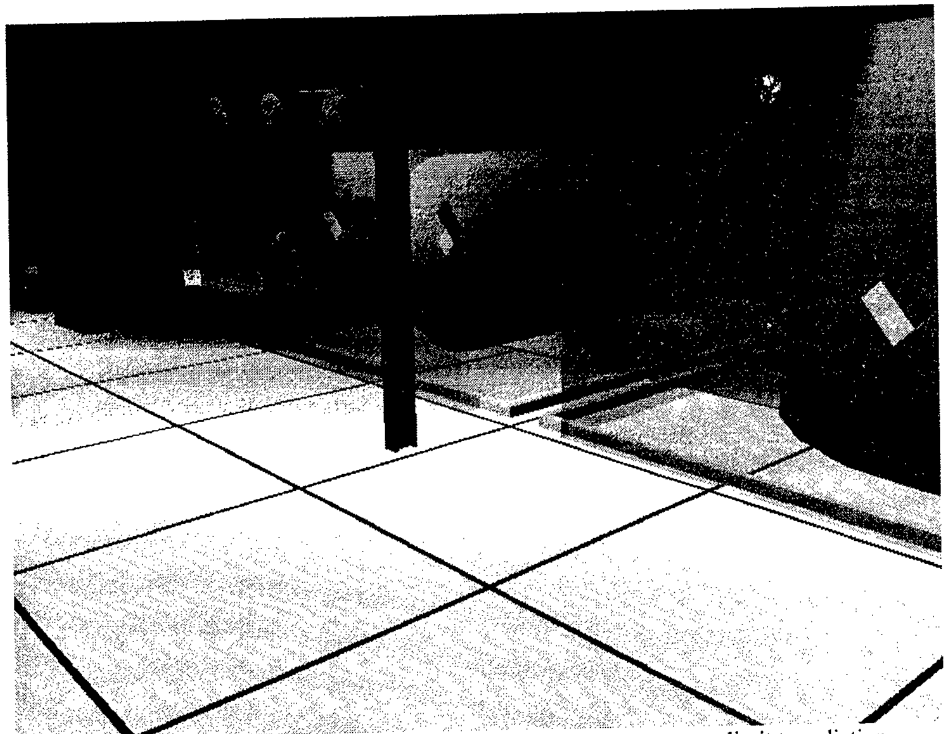

Figure 3. A Hazardous Radius Shell defines the maximum exposure limit to radiation.

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